The lack of variability of the iron line in MCG–6-30-15: general relativistic effects

G. Miniutti[1][*], A.C. Fabian[1], R. Goyder[2] and A.N. Lasenby[2]

[1] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA*
[2] *Astrophysics Group, Cavendish Laboratory, Madingley Road, Cambridge, CB3 0HE*

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ABSTRACT
The spectrum and variability of the Seyfert galaxy MCG–6-30-15 can be decomposed into two apparently disconnected components: a highly variable power law and an almost constant component which contains a broad and strong iron line. We explore a possible explanation of the puzzling lack of variability of the iron line, by assuming that the variations of the power law component are due to changes in the height of the primary source in the near vicinity of a rotating black hole. Due to the bending of light in the strong field of the central black hole, the apparent brightness of the power-law component can vary by about a factor 4 according to its position, while the total iron line flux variability is less than 20 per cent. This behaviour is obtained if the primary source is located within 3–4 gravitational radii ($r_{\rm g}$) from the rotation axis with a variable height of between ~ 3 and $8\ r_{\rm g}$. These results revive the possibility that future X–ray observations of MCG–6-30-15 can map out the strong gravity regime of accreting black holes.

Key words: accretion discs — black hole physics — line: profiles — X-rays: general

1   INTRODUCTION

The X–ray spectrum of the Seyfert 1 galaxy MCG–6-30-15 exhibits a broad emission feature peaked at 6.4 keV which extends from below 4 keV to approximately 7 keV, and was first resolved with ASCA (Tanaka et al. 1995). The profile of this feature is consistent with that expected from iron fluorescence from the surface of an accretion disc surrounding a massive black hole.

The X–ray continuum emission of MCG–6-30-15 is highly variable (see e.g. Vaughan, Fabian & Nandra 2003; Fabian & Vaughan 2003). Since the reflection features, such as the observed iron line, are expected to be due to reprocessing of the hard X–ray continuum by dense gas in the accretion disc (George & Fabian 1991; Matt, Perola & Piro 1991), the line flux should respond to the changes in the illuminating continuum (Reynolds et al 1999). Line flux variations have been reported on timescales of about 10^4 s, but with a much smaller amplitude than the observed continuum changes (Iwasawa et al. 1996; Vaughan & Edelson 2001; Shih, Iwasawa & Fabian 2002; Fabian & Vaughan 2003). Furthermore, the variability of the iron line flux and the observed continuum are uncorrelated.

The source spectrum and variability can be explained

by a two component model (Shih, Iwasawa & Fabian 2002) consisting of a variable power-law component and an almost constant reflection component containing the iron line. This model successfully accounts for the behaviour of MCG–6-30-15 during a 320 ks long *XMM–Newton* observation (Fabian & Vaughan 2003). Hereafter, we shall refer to these components as the Power Law Component (PLC) and the Reflection–Dominated Component (RDC). The existence of a varying soft component with a spectral shape uncorrelated with flux together with an almost constant harder component is also evident in the linearity of the flux–flux relationship recently presented by Taylor, Uttley & McHardy (2003).

The extreme red wing of the iron line indicates that the inner radius of the disc extends down to only a few gravitational radii (Wilms et al 2001; Fabian et al 2002). Strong gravitational field effects dominate the behaviour of photons in this region with not only gravitational redshift being severe but also gravitational light bending (Martocchia & Matt 1996; Martocchia, Karas & Matt 2000; Dabrowski & Lasenby 2001; Martocchia, Matt & Karas 2002). Fabian & Vaughan (2003) have recently suggested that changes in the position of the power–law emission region could lead to large variations in the observed flux together with a strong and almost constant reflection component, containing the broad iron line. This behaviour would be due

predominantly to strong light bending, which is expected if the primary source is located close to the central black hole and illuminates the inner regions of the accretion disc, as the shape of the iron line suggests. As the source approaches these regions of the disc close to the black hole so more radiation is bent away from our line of sight and intercepted by the disc. Such light bending also explains the high observed equivalent width of the line.

In this Letter, we investigate, for the parameters relevant to MCG–6-30-15, the variability of the PLC and of the RDC as a function of the position and state of motion of the primary X–ray source, seeking solutions that allow for a strongly varying PLC and an almost constant RDC. The main purpose of this work is to provide an astrophysical context in which the two component model for the variability of MCG–6-30-15 can be explained self–consistently. Our calculations are performed using a combination of Monte Carlo and ray-tracing methods that take into account the effects of Doppler/gravitational redshifts and light beaming/bending on the motion of photons in the spacetime of a rotating black hole.

2   MODEL AND ASSUMPTIONS

The observed broad iron line profile and its extended red wing (Wilms et al. 2001; Fabian et al. 2002) imply that most of the emission originates at radii less than $6r_g$ ($r_g = GM/c^2$), suggesting that the central black hole is rapidly spinning (Iwasawa et al. 1996; Dabrowski et al. 1997). Our computations are then performed in the spacetime of a maximally rotating (Kerr) black hole.

The accretion disc is assumed to be thin and to lie in the equatorial plane, perpendicular to the rotation axis. The accreting material is flowing along stable circular geodesics and the disc extends from the radius r_{ms} of the marginal stable circular orbit (e.g. Novikov & Thorne 1973) out to $r_{\mathrm{out}} = 100 \ r_g$.

The source of primary hard X–rays is assumed to have a ring–like axisymmetric geometry and is located above the disc at a distance ρ_s from the rotation axis and at height h_s, related to the Boyer–Lindquist coordinates r_s and θ_s of the source by $r_s = \sqrt{\rho_s^2 + h_s^2}$ and $\theta_s = \arctan(\rho_s/h_s)$. The source can be both static or corotating with the disc. If the source is static, its 4–velocity has to be proportional to the time–like Killing vector of the spacetime so that

$$\mathbf{u} = C_{\mathrm{stat}} \, \partial_t \ , \tag{1}$$

while if it is corotating one has

$$\mathbf{u} = C_{\mathrm{corot}} \, (\partial_t + \Omega \partial_\phi) \ , \tag{2}$$

where $\Omega \equiv 1/[a + (r \sin \theta)^{3/2}]$ and where C_{stat} and C_{corot} are found by requiring that the source follows a time–like world line ($\mathbf{u} \cdot \mathbf{u} = -1$).

The case of a static source is investigated mainly for comparison with the corotating one that we consider physically more plausible. This is because since flares are believed to be associated with magnetic activity of the disc, they are more likely to be corotating with the accreting material rather than static. In the case of a corotating source, since the orbital timescale in the vicinity of the central massive black hole is much shorter than the integration time needed

in observations, any information on the azimuthal position of the flare is lost. This justifies our choice of a ring–like axisymmetric source rather than a point–like whose azimuthal position would affect the iron line profile emitted from the disc but is unobservable with current long observations.

The source produces isotropic emission in its proper frame with a power law luminosity $L_s = L_0 E_s^{-\alpha}$, where E_s is the photon energy in the source comoving frame and the spectral index is chosen to be $\alpha = 1.1$, consistent with the observed photon index in the spectrum of MCG–6-30-15 (see e.g. Fabian & Vaughan 2003). Isotropic emission is enforced by using the HEALPix[1] (Hierarchical Equal Area isoLatitude Pixelisation) package which allows one to define equal area curvilinear quadrilaterals on the sphere. Isotropy (in the source proper frame) is obtained by sending photons along the directions defined by the geometrical centre of each quadrilateral.

The photons emitted by the primary source illuminate both the accretion disc and the collecting area of a distant observer, whose distance from the source is taken to be $r_{\mathrm{obs}} = 10^3 r_g$ for numerical purposes. The observer measures both the direct flux and the reflected emission from the disc. The observer inclination has been fixed to 30 degrees, which is appropriate for the case of MCG–6-30-15.

In this work, we assume that the direct continuum emission from the primary source dominates over the reflected continuum emission, which is neglected in our computations. However, since the reflected continuum varies together with the iron line, it does not affect the results on the variability of the PLC and of the RDC (hereafter represented by the iron line only), which are the main purpose of this Letter.

Each simulation is carried out by sending a given number N of photons from the primary source and by integrating along the null geodesics in the Kerr spacetime until the photons reach the accretion disc (or are lost into the black hole horizon) or the observer collecting area. This procedure allows us to compute directly the PLC at the observer and the illuminating flux on the disc as a function of the photons incident angle θ_i and energy E_d, taking into account both special and general relativistic effects.

The iron line local intensity is computed by assuming that the fluorescent photons are produced by cold, non–ionised matter at the rest frame energy of 6.4 keV and by making use of the work by George & Fabian (1991) who provided analytical approximations for the dependence of the fluorescent emission on θ_i and E_d (see also Ruszkowski 2000; Lu & Yu 2001 for further details). In this work, the iron line emission is assumed to be isotropic in the rest frame of the disc, which is not a strong limitation for low inclination objects such as MCG–6-30-15.

To calculate line profiles and fluxes, we use a ray–tracing technique to follow the trajectories of photons from the observer until they either intersect the accretion disc or the black hole horizon and we calculate the redshift factor corresponding to each arrival position on the disc (Laor 1991; Dabrowski et al. 1997). Then the line flux is obtained by making use of the relativistic invariance of I_ν/ν^3, where I_ν is the specific line intensity, and by integrating over the solid angle subtended by the whole disc at the observer.

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[1] see http://www.eso.org/science/healpix
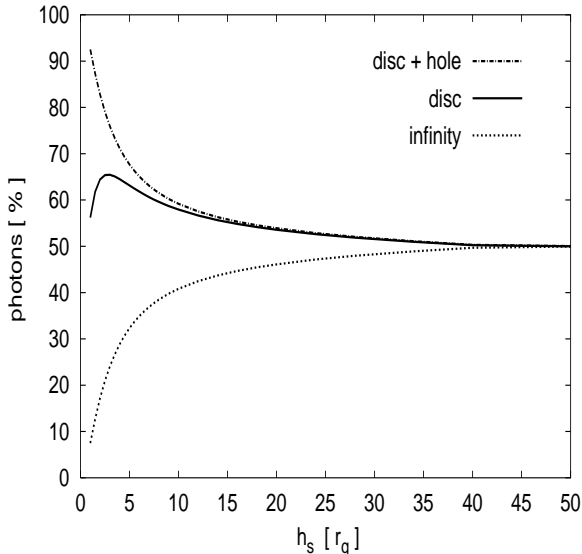
Figure 1. The percentage of the photons emitted by the primary source that reach the accretion disc or that are able to escape at infinity is plotted as a function of the source height above the equatorial plane. As a reference, the photons that either reach the disc or are lost into the black hole horizon is also shown. The source is static and it is located at a distance $\rho_s = 2.0\ r_g$ from the rotation axis. The outer radius of the accretion disc is, in this case, chosen to be $r_{out} = r_{obs}$.

3 PLC AND RDC VARIABILITY

We investigate the effects that the position and the motion of the primary source have on the continuum and reflected observed fluxes, with particular emphasis on the associated variability of both the PLC and RDC components.

As already pointed out in previous studies (Martocchia & Matt 1996; Martocchia, Karas & Matt 2000; Martocchia, Matt & Karas 2002; Dabrowski & Lasenby 2001), if the primary source is very close to the central massive black hole, a large fraction of the emitted photons will be bent onto the disc (or lost into the hole event horizon), reducing the observed direct flux with respect to the reflected one and enhancing the iron line equivalent width (EW).

This effect is shown in Fig. 1 where we consider the arrival positions of the photons emitted from a static source located at $\rho_s = 2.0\ r_g$ as a function of the height (h_s) of the source. As an example, for a source height of $h_s = 2\ r_g$, the percentage of photons that reach the accretion disc is 64 per cent. The remaining 36 per cent is equally distributed between photons that are lost in the hole horizon and those that reach the observer at infinity. Similar results are obtained also in the case of a corotating source. However in the latter case, fewer photons are lost into the hole horizon (8 per cent) due to the strong beaming in the direction of the source motion that reduces the number of photons directed towards the hole. The illumination pattern on the disc is then more extended for a corotating source (74 per cent of the photons hit the disc) than for a static one.

Here, the PLC variability is supposed to be caused by variations of the primary source position. Since the source
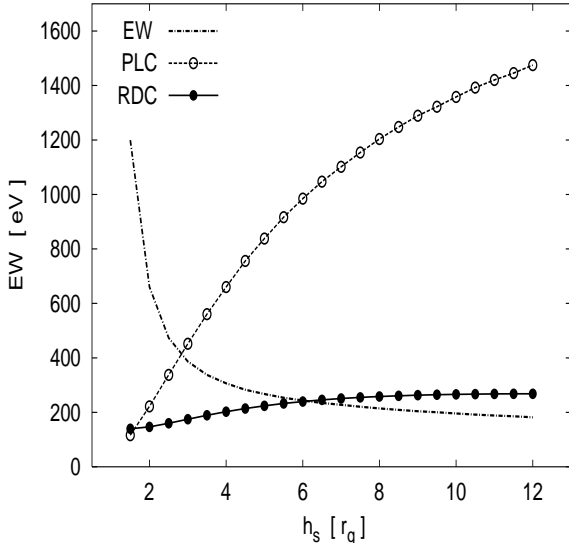
Figure 2. PLC and RDC components as a function of the source height. The iron line EW $\equiv$ RDC/PLC is also shown. The source is static and it is located at $\rho_s = 2.0\ r_g$ from the rotation axis. Units of flux are arbitrary while the EW is given in eV.
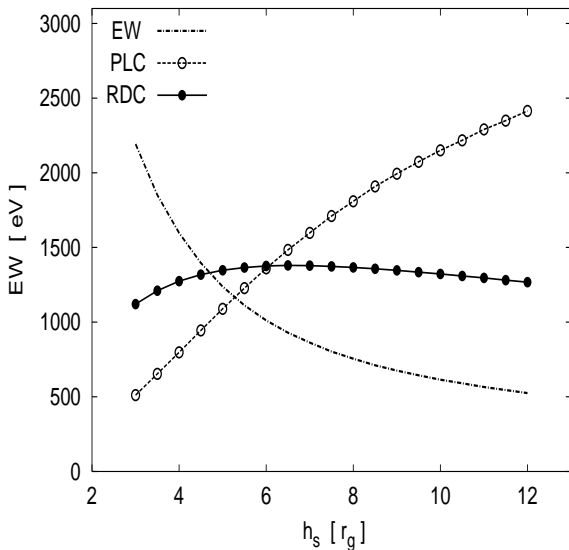
Figure 3. Same as Fig. 2 but for a corotating source at $\rho_s = 2.0\ r_g$.

height controls the amount of direct radiation that reaches the observer (see Fig. 1), the observed PLC from a source close to the black hole is much smaller than that of a source located at larger height. At the same time, the RDC responds to a much larger region than the PLC, especially if the source is corotating, and it is likely to vary less than the power law component.

To illustrate this behaviour, and to compare the variation of the two components we present results for sources located at $\rho_s = 2\ r_g$ from the rotation axis, but similar results can be obtained within $\rho_s \simeq 3 - 4\ r_g$. In Figs. 2 and 3 we show the PLC and RDC fluxes as a function of the source height for a static and a corotating source respectively. The
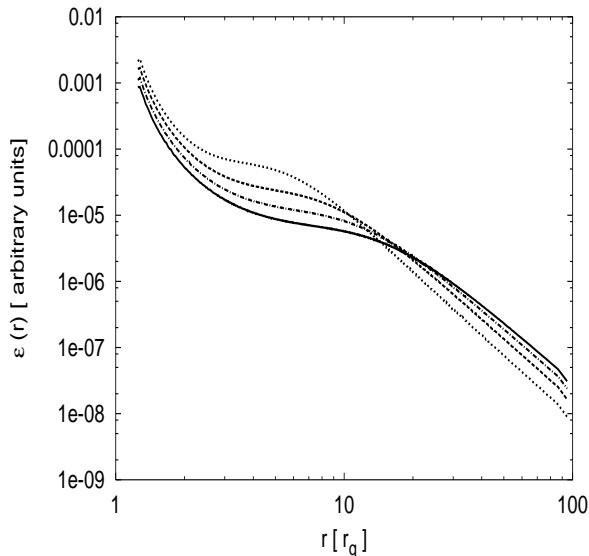
Figure 4. The local iron line emissivity profile on the accretion disc for a corotating source at $\rho_s = 2.0 \, r_g$ is shown for different values of the source height. Looking at the right side of the plot the source heights are, from bottom to top, $h_s = 4, 6, 8, 10$.

PLC flux is defined as the observed flux of the power law component evaluated at 6.4 keV, while the RDC is the total iron line observed flux (i.e. the integral over energy of the line). We also show the iron line equivalent width defined as the ratio between the RDC and the PLC. The general behaviour is that the variation in EW is dominated by the PLC variability and is clearly anti–correlated with flux. Since we neglect the contribution of the reflected continuum, the values of the line EW are overestimated, especially in the most extreme cases (low source height) and they have to be taken only as an indication.

Both the power law and the reflection–dominated components vary with the height of the primary source, but the variation of the RDC has a much smaller amplitude. This behaviour is enhanced in the corotating case shown in Fig. 3 where, if the source height changes from 3 to 8 r_g, a variation of the PLC by almost a factor 4 is accompanied by a variation in the RDC with a maximum amplitude of 15 per cent around its mean value. Even larger variations of the PLC are found for smaller values of ρ_s, together with an almost constant RDC. These results can be compared with the work by Fabian & Vaughan (2003) who analysed the spectral variability of MCG–6-30-15 finding variations of the RDC up to about 25 per cent within a PLC change of about a factor 4.

We note here that the two component model also accounts (Vaughan et al 2003, in preparation) for the shape and amplitude of the r.m.s. variability spectrum of MCG–6-30-15, plotted in Fabian et al. (2002).

3.1 Emissivity and line profiles

We compute the local iron line emissivity profile induced by a ring–like primary source by rotating the illumination pattern of the one for a point–like source over the azimuthal position on the disc. The emissivity is thus axisymmetric and
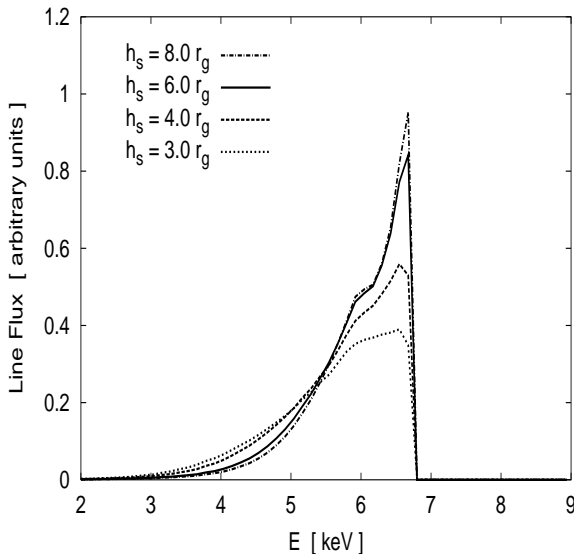
Figure 5. Iron line profiles for a corotating source at $\rho_s = 2.0 \, r_g$ and for different source heights.

it is a function of the radial position on the disc only. The emissivity $\epsilon(r)$ produced by a corotating ring source at $\rho_s = 2 \, r_g$ is shown in Fig. 4 for four different source heights. Due to the anisotropy of incident radiation (controlled by h_s), the emissivity in the inner regions is reduced by increasing the source height, while it increases in the outer disc (see also Martocchia, Karas & Matt 2000).

At a fixed h_s, the emissivity is steeper in the inner disc than in the outer regions with a transition region between about 3 and 10 r_g. This is in good agreement with a recent analysis (Fabian et al. 2002) where a best fit to the iron line of MCG–6-30-15 was found by using a broken power law emissivity with a break radius of about 6 r_g. The outer emissivity index was found to be ~ 2.5, while a steeper index of about ~ 4.8 was derived within 6 r_g.

The iron line profiles are broad with an extended red wing if the primary source is located close to the black hole, while the profile becomes progressively narrower as the distance from the hole is increased. This is due to the different illumination pattern on the accretion disc (and different emissivity) for different source heights. If the source is low, the inner regions of the disc are more illuminated resulting in the enhancement of the relativistic broadening of the iron line. Our model then predicts broader line profiles when the source flux is low (source at low heights). This is indeed the sense of the changes seen in the ASCA 1994 observation (Iwasawa et al. 1996). In Fig. 5 we show the line profiles obtained in the case of a corotating source at $\rho_s = 2.0 \, r_g$ for different heights in the range $3 - 8 \, r_g$, whose variation accounts for a change in the PLC by a factor ~ 4.

The changes in the line profiles for different source heights are subtle and it could be difficult to detect them in real X-ray data. If this is the case, an observer would conclude that the line is almost constant both in flux and in spectral shape while the PLC varies in normalisation, as it seems to be the case in the recent *XMM-Newton* observation of MCG–6-30-15 (Fabian et al. 2002) that was used to study the source variability (Fabian & Vaughan 2003). This

possibility has been tested by comparing the line profiles we produced with this same data set. We analysed the 3–10 keV time–averaged spectrum obtained with the EPIC pn camera using XSPEC version 11 (Arnaud 1996). The spectrum was fitted using a simple power law plus the relativistic line produced by our model when a corotating source is placed at $\rho_s = 2.0\ r_g$ with variable height between 3 and 8 r_g.

The χ^2 difference between the two more extreme heights is $\Delta\chi^2 \simeq 13$ with $\chi^2 = 265.8$ for $h_s = 3\ r_g$ and $\chi^2 = 252.9$ for $h_s = 8\ r_g$, both with 178 degrees of freedom. However, this simple model leaves some residuals around 6.4 keV and the significance of the preferred source height is poor. These residuals can be accounted for by an additional narrow Gaussian component with an equivalent width of only ~ 30 eV that can be due to reflection from distant material and is not included in our model for line emission from the inner 100 r_g of the accretion disc. With the addition of this component, the emission line in the *XMM-Newton* data is well fitted by our model and, most remarkably, the χ^2 for the most extreme heights is now identical (both models have $\chi^2/\nu = 190.5/175 \simeq 1.09$).

This means that, once the narrow line component is included, the changes in the line shape are substantially reduced and may be difficult to detect with current instruments. If the narrow component is emitted from distant material, it is likely to remain constant. Future observations of the source may be capable of resolving the narrow component from the broader one emitted from the accretion disc, allowing more stringent constraints to be placed on the height of the illuminating primary source. In summary, the model we have explored consistently accounts for the uncorrelated variability of the PLC and RDC components and produces also iron line profiles in good agreement with the most recent X–ray observation of MCG–6-30-15.

4   CONCLUSIONS

The spectral variability of MCG–6-30-15 can be explained by an almost constant Reflection–Dominated Component together with a highly variable Power Law Component.

Here we have explored a model in which the variability of the PLC is accounted for by changes in the height of the primary source above the accretion disc. Light bending by the gravitational field of the black hole substantially reduces the PLC flux at low heights, allowing for high continuum variability. The iron line flux, which represents the RDC, is much more constant with an amplitude of variation of about 15–20 per cent when the PLC varies by a factor ~ 4.

It should be noted that the region where the flare (or multiple flares) creating the PLC should be located to reproduce this behaviour is close to the rotation axis, within 3-4 gravitational radii. It is most plausibly powered by magnetic fields from the disc, possibly linking to the hole (e.g. Blandford & Znajek 1977; Wilms et al 2001), and perhaps forming the base of a jet (note that the radio emission from MCG–6-30-15 is weak and unresolved, Morganti et al. 1996).

We also find that the iron line emissivity on the accretion disc is consistent with a broken power law profile with a transition between about 3 and 10 r_g, in good agreement with recent observations.

In summary, the strong light bending close to the black

hole can cause the PLC and RDC to appear disconnected. Even if the source of the PLC is intrinsically constant in luminosity, it will appear to an outside observer to vary if its height from the disc changes. Much of the radiation is bent onto the disc in a manner which means that the flux of the RDC will appear constant. Subtle profile changes are expected in the sense that the line will appear narrower when the PLC is bright and broader when dim, but they are difficult to detect with current instruments.

It is of course possible that the source of the PLC undergoes intrinsic luminosity variations on both short and long timescales. These will lead to connected variability between the PLC and RDC, and reverberation on short timescales. For MCG–6-30-15 these timescales are probably less than 10^3 s, too short to be investigated with XMM-Newton but within the grasp of Constellation-X.

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